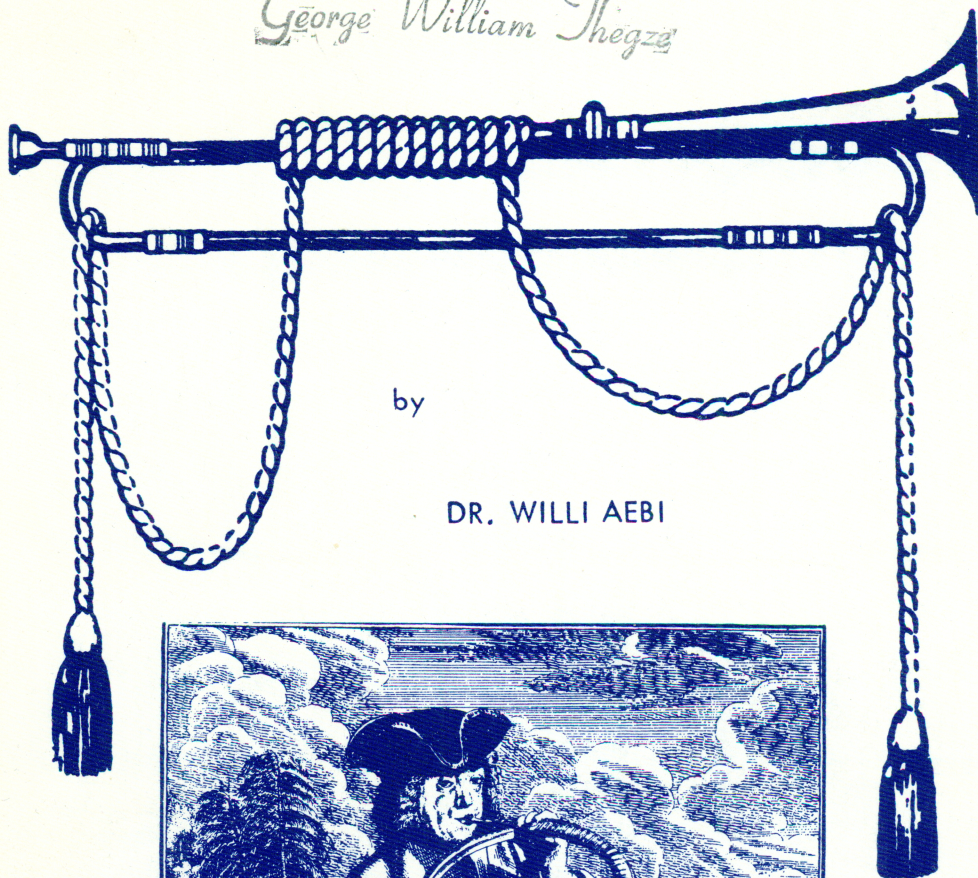


# THE HORN AND ITS INNER ACOUSTICS

*George William Theggs*



by

DR. WILLI AEBI





*George William Shuman*

## THE HORN AND ITS INNER ACOUSTICS

by

DR. WILLI AEBI

Among orchestral instruments, the horn has a special place. Schumann said, "The horn is the heart of the orchestra." The horn is very much valued because of its special tonal character but it is also very much feared because it sometimes produces false tones (in German called "kiekser," in French "canards"). The writer has been playing this ticklish instrument as an amateur hornist for over ten years and knows the problems regarding tone and blowing techniques. For the past several years he has carried out extensive acoustic studies and has obtained most interesting results. Following a short historical introduction and a summary of the brass instruments in use today, the results of these studies will be reported.

### A. THE HISTORICAL DEVELOPMENT OF THE HORN

About 1700 the horn was introduced into the orchestra. Since then the music has gone through various transformations; however the orchestra itself, apart from its numerical size, has been changed relatively little. It was developed through the Mannheim-Schule during the Baroque period with the cembalo as a general bass instrument. About 1750 the cembalo was retired and the clarinet was introduced to produce the tone of Vienna-classic and Romantic music. With the improvement of brass instruments by the introduction of the valve mechanism for horn and trumpet, and also the completion of the Wagnerian tuba after 1850, the magnified ensemble of instruments of the modern symphony orchestra was finally born.



*George William Lloyd*

During this period, the stringed instruments had remained practically unchanged.

The woodwinds and trombones underwent technical improvements which had no influence on their intonation. The valve mechanism was introduced to the trumpets in 1850 and thus the trumpets became chromatic instruments. Before this only the natural tone was used. The horn also had valves in 1850 but before another 100 years had passed a very important change was made. Therefore, the history of the development of the horn is divided into three stages or periods; Baroque from 1650 to 1750, Vienna-classic and Romantic from 1750 to 1850 and from 1850 to the present.

#### 1. The "Corno da Caccia" [Picture 1]

This is a horn of the first period mentioned above (Telemann, Bach, Händel) and corresponds to the hunting horn which is played even today, particularly in France (trompe de Chasse). It is often played without putting the right hand into the bell and, according to the old pictures, it was played with the bell lifted. This horn produces only the natural tones.

#### 2. The Inventionshorn

During the second period of the horn, beginning in 1750, Josef Hampel, the hornist in Dresden, founded the technique of "Stopfen" with his right hand in the bell.

Two different effects are obtained by putting the hand into the bell. The effect stops when the hand is inserted to a limited extent as the acoustical length of the tubing is elongated. As a result, the tone becomes flat down to one whole tone.



When the opening of the bell is closed by inserting the hand further inside the bell, the tone jumps one-half tone sharp and sounds very shrill like an echo much damped. This effect is physically explained by the results of this research. Hampel also made an important improvement in the Inventionshorn. As shown in picture 2, it consists of a bent tube located inside the circle of the branch with the mounting socket. There are different lengths of these tubes. By changing this tube, this instrument can be tuned to different keys. Also small deviations in pitch are controlled by adjusting the tubing.

Using the stopf-technic, the stiff natural tone scale is broken because the tone can be shifted to the extent of a half-tone to one full tone flat with a distinctly different sound. Due to this ability to lower the tone, the melodic potential being extended caused the horn to be used more frequently as a solo instrument in the compositions of the "Mannheimer Schule." As the Inventionshorn was very well accepted in the orchestra, it maintained its place a long time after the introduction of the valve horn. In 1844 Wagner wrote Tannhauser with two Inventionshorns and two valve horns. Brahms also favored it because of its special tonal quality. At the Conservatoire in Paris lessons for the valveless horn were continued until 1897. The interval between 1750 and 1850 was the golden period of horns.

### 3. The Valve Horn

Even if the hornists could apply the stopftechnic with unusual skill, compositions such as Fidelio (1804) and the Ninth Symphony (1823) of Beethoven and the

early Wagner operas needed the technical completion for this instrument.

This completion was achieved in the horn by applying the valve mechanism which was introduced generally in 1850. With this, the third and last period of development for the horn was completed and it finally became a chromatic instrument.

The valve mechanism was invented between 1810 and 1830 and at the same time three different constructions were developed which are maintained even today. They are applied to the following three different types of horns whose tone qualities are also different:

a) The Viennese horns (Die Wienerhörner): The Philharmonic Orchestra of Vienna today blows the Wienerhorns with Stechbüchsenventil [picture 3].

They sound very soft and at performances of Romantic works such as Wagner, Brahms and Richard Strauss give the horn registers an especially ripe sound.

They are used almost exclusively in F.

b) German horns with Rotary Valve: They are used for the most part in Germany and the Anglo-Saxon countries. Their sound is bright and especially good for performances of classic works such as Mozart and Beethoven.

c) The French horns with Stöpselventil (Perinet-Ventil, Piston): They have a sound still bright like a hunting horn and are played in the Latin countries and Russia, often with a sophisticated vibrato. To the ears of German people, their sound is somewhat thin; the French still prefer the sound of the hunting horn.



#### 4. Sound and Basic Key of Horns

Since the first 20 years of our century, the basic key used in these horn groups has caused differences in tonal characteristics. Due to "perfectionism" which is demanded in orchestras, hornists have become used to playing horns with high basic keys, such as high Bb and high F, in order to produce the high notes more reliably. The delicate ear hears this as a difference in tonal quality; the high horns speak very easy but the sounds in the middle and low registers are no longer soft as in an F horn. Dr. Jürgen Meyer, Braunschweig, has reported on these differences of tonal quality in his excellent publication [1]. The difference of tone outside the instrument is designated as "outside acoustic" and the vibration phenomena of the brass are designated as "internal acoustic."

#### B. SMALL NOTES ABOUT THE ACOUSTICAL PHYSICS

The literature about the shape and length of static waves in wind instruments is only found in recent publications, notwithstanding some past works about the vibration characteristics of the pipes in a pipe organ reported in 1849 by the French organ maker, Cavaille Coll (1811 to 1899) in "Academie des Sciences." There were also researches to improve the intonation of brass instruments [2] as well as relevant theoretical works. Two excellent works exist, one by the gifted English physician, Lord Rayleigh (1842 to 1919) [3] and the other by H. Bouasse [4]. However, through such publications, instrument makers and orchestra players do not get a picture of the basic phenomena of vibration in wind instruments. This is the reason the author is relating the details of his experimental studies about the "internal acoustics" of the French horn.

The vibration phenomena in the horn can be grasped mathematically. However, the great difficulties of inducing the vibration are not treated here. The results of the researches regarding the French horn are described; the meaning and the clarification of the many interesting problems encountered are left to the field of the Science of Acoustics. Sound, as it is perceptible to the human ear, depends on vibration resulting in pressure against and movement of the air.

At  $20^{\circ}$  centigrade, the vibration produced by shooting a gun moves through the calm air at a speed of  $c = 343.8\text{m/s}$ . The original pressure induces vibrating sound waves at regular intervals and sound is thus produced. The lower limit to which the human ear is sensitive is 16 vibrations per second (vps) and the upper limit is 20,000 vps.

The difference between the oscillation of the air at the fixed point and the transportation of the oscillation to the portions which carry the pressure vibration must be viewed differently when considering acoustical vibration. This is a continuous sound wave which is compared to the surface wave of water. This sound wave, when it is carried within a unit second to the distance of 343.8m, has an oscillation frequency (f) per second for each constant tone. At the Kammertone  $a'$  it is 440. The length of oscillation of the sound wave is the f portion of the continuous sound wave. At the Kammertone  $a'$ ,  $\lambda = 343.8 : 440 = 0.78\text{m}$ . The product of wave length  $\lambda$  and frequency (f) shows the speed of the sound wave:  $f \cdot \lambda = c(\text{m/s})$ .

In acoustics, the standing wave is distinguished from the above described wave. According to general opinion, they arise through superimposing continuous waves of the same frequency and in a counter direction. Also they are generally formed only in bounded space and are reflected at the boundary surface of that space.

The air column in the tubing of a wind instrument vibrates when blown and in that way the sound is formed. With the flute, the vibration is started by the air stream against the edge of the mouth hole; for the clarinet, at the reed; for oboe and bassoon, at the double reed of the mouthpipe. For the French horn, trumpet and trombone, the vibration is generated through the lips. According to the above mentioned general opinion, the sound waves are reflected when they reach the open end through the inside tubing. The going-out waves and the reflected waves are superimposed and then the standing waves are formed. Contrary to the transverse vibration of string, the vibration of the air follows along the axial direction of the tubing. As long as a tone of constant loudness is generated, the stationary standing wave is formed, i.e. the vibration of the air particles is the same at every place. Along the longitudinal axis, the stationary vibration changes regularly between minimum and maximum. The place of maximum movement is called the loop of vibration; that of minimum movement, the node of vibration.

The vibration phenomenon of the standing waves is easily understood by observing the portion of air column between the neighboring loop. The node of vibration



in a cylindrical tube is located in the center; in a conical tube it is, according to Lord Rayleigh, shifted to the side of the smaller diameter. The width of the vibration increases from the node to the loop until it reaches its maximum. So the air column in both parts oscillates from right to left to the node against one another, with the amplitude which is increasing to the outside direction. It is not possible to measure the width of the vibration directly, but by calculation it is about  $3 \cdot 10^{-5}$  mm at the loop in the case of 1000-Hz-tone of normal loudness. When both parts of the air column vibrate to the outside direction, the pressure falls down at the node in between until they come to the most external stage. When the parts of the air column are in the most internal stage, the pressure increases at the node up to its maximum. This fluctuation of pressure is designated as "sound pressure." "Fluctuation of the pressure" usually is used in describing the sound field but according to the terminology adopted for practical acoustics in 1959, this is now described as "sound pressure." [Definition 14 of Acoustical Committee, Din 1322 July 1959 "Sound Pressure": pressure alternation due to sound vibration.]

This terminology for the pressure is attributable to the fact that measuring the pressure is the best approach for the analyzation of different sound fields and it is through alternation of pressure that we recognize sound.

The human organ of hearing enables man to recognize and distinguish the phenomenon of sound according to its loudness, tone height, tone quality and also the direction from which the sound arises. Sound pressure is measured by

using an electrical sound receiver. A condenser microphone is adaptable as a sound receiver and its sensitive responses can be absolutely calculated through compensation [5]. The difference in sound pressure along the axial direction of the tubing of musical instruments can be confirmed through the microphone and control unit. Through this measuring, the place of maximum and minimum pressure, i.e., the location of the loop and the node of vibration, is analyzed [picture 9].

In physics, the complimentary factor to the vibration phenomenon of sound is the velocity or the mean speed of the oscillation of air particles. At the loop of the vibration, the velocity becomes maximum while the sound pressure drops to the minimum. The difference in the velocity along the axial direction of the tubing is measured by the "hot wire sonde." This instrument consists of a fine electrically heated wire which is cooled by the passing air stream according to its speed. Through the difference in cooling rate, its electrical resistance is changed and this can be measured. Therefore, standing waves in musical instruments can be analyzed according to the change in sound pressure and velocity. Picture 9 is the velocity curve compared with the sound pressure curve which is shifted  $1/4$  wave length. Maximum velocity always locates between two maximum pressures. In this experiment, measurement by "hot wire sonde" was not applied as the location of the loop of vibration can be measured through the sound pressure diagram.

The acoustical wave, standing or continuous, is always bounded by two layers vertical to the sound direction in which the air particles have motion of equal quantity and direction.

The transient pressure in this layer is also the same. At the standing wave in the tubing, entire portions which move with the same frequency exist both in the maximum point of their movement and the middle point of their movement at the same time. In acoustics, it is said that they are in the same phase when the direction of movement is changed in the part which is bounded by the node of vibration.

As already explained, there are nodes of vibration with minimum motion and maximum pressure between loops of vibration with maximum motion. They exist also in the boundary surface from which the vibrating air is reflected and also in the boundary ground of the so-called "gedeckt or gedackt" pipe of an organ and, as will be shown in this experiment, the inner surface of the hand which "stop f" the French horn like a mute. The analysis for these is new and worthy of note.

Bounding the air column by a solid wall is defined in acoustics as "hard boundary." On the contrary, the open ends of wind instruments and organ pipes are termed "soft boundary." At the boundary the loop of vibration and the standing vibration continually transform into the continuous sound wave of the outside field.

A full acoustical wave length is the distance between a node and the second node following it. In the middle node, the momentary pressure is deemed to be over or under the mean when the pressure at both outside nodes is under or over the mean pressure. The momentary pressure at two neighboring nodes is always opposite. The fluctuation of the pressure of neighboring nodes is, however, almost the same. For this reason, the measurements of the sound pressure of neighboring nodes show similar values.

The best way to observe the vibration phenomenon and to measure the sound pressure is to study the moving characteristics of a pair of loop and node or node and loop vibrations.

The velocity of partial air and the pressure at a given place vary as an oscillation along with the time. It is essential to find out whether they reach their maximum at the same time or one after the other. In the mathematics of acoustics, the situation of phase of pressure and velocity vibration is treated. The total phenomenon of vibration is classified by the phase angle with  $360^\circ$ . At the final stage of vibration of parts the angle is  $180^\circ$ , corresponding to the beginning. At the extreme stage, where the velocity has vanished, the sound pressure reaches its maximum. On the other hand, the maximum velocity is obtained at the middle point of pressure. This occurs periodically a quarter of a vibration earlier. It is determined that the phase difference between velocity and pressure in the tubing is  $90^\circ$ . On the contrary, with the continuous sound wave, the velocity and pressure reach their critical value at the same time. The transformation of the standing wave inside the tubing into the continuous wave of the outside, is achieved in the bell. This is named the rotation of velocity-phase of  $90^\circ$  in the bell.



## C. THE ACOUSTICS OF THE FRENCH HORN

### 1. The Natural Tone Series

The people who hear folk music being played in Switzerland are surprised to find out that the alphorn player can play the music without holes, keys or valves.

Johannes Brahms congratulated Clara Schumann on her birthday with this kind of melody on 12 September 1868 [picture 4]. The masterly theme is found in the andante of the fourth movement of his 1st Symphony (completed in September 1876). These notes come from the natural tone series which can be produced by alphorn, hunting horn, Inventionshorn and every brass instrument [picture 5].

There are many examples of this kind in the works of Bach, Handel, Haydn, Mozart, Beethoven and Weber. They are a real treasure house for one who can understand their value.

Modern horns with valve mechanisms are included in this series. The technique of the hornist depends upon his finding the correct notes through the corresponding tension of his lips.

The physical background of this series depends on the rule of physics according to which the frequencies of all tones are multiples of a fundamental tone. As stated before, it is difficult for the hornist to blow the 1st tone and therefore it is not used in compositions. The harmonics of 7. 11. 13. and 14. deviate considerably from the diatonic scale and the ear of European people feels something wrong in them. They are found, however, in baroque compositions and in the tunes for the Corno da caccia and Clarino trumpets. It is not clear whether the players of

that time could correct the tone through changing the embouchure. After 1750 it became possible for the hornist to correct these notes by applying the "stop f" technic (developed by Hampel) with the right hand. On the hunting horn which is played in France without stop f technique even today, these notes are played especially in fast passages. The alphorn player also blows the 11th although its sound is apparently too sharp. It is named "Alphorn-Fa." It is so much liked by the Jodel singers of Innerschweis that they still sing today with this instrument.

In the "Serenade for Tenor, Horn and Orchestra" by Benjamin Britten, Opus 31, which was dedicated to the best hornist of our age, Dennis Brain [died 1937], the natural tone of 7. 11. and 13. are many times applied in the introduction as horn solo. Also in the "Ring" by Richard Wagner, horns without valves are used for the Siegfried theme of purely natural tones and the effect is most impressive. The Siegfried motive in the 14th act must be played by a horn in the orchestra because it contains the tones of h', a', f'' and f' which are not found in the scale of the natural horn. As a result, a wonderful effect is introduced through the contrast between the tragic Siegfried motive and the wild horn motive blown on the stage.

The sounds of the natural tone scale could be applied variously by composers because they produce the major cord. Therefore, the basic key of the horn was chosen in accordance with the key of the music. During this period, the practice of writing the horn part in "C" originated. When the tonality of the music changes, the hornist must change his instrument. Today the hornist of a valve horn keeps the same instrument and transposes the written music. If the music is written for the Eb horn, he transposes his F horn a whole tone lower than the

written notes and for his A horn he would transpose a major third higher. The hornist with a Bb or high F horn transposes correspondingly with suitable valve fingering.

The cleanness of the natural tone series (except the 7. 11. 13. and 14. harmonics) depends upon the inside shape of the tubing. The bending of the tubing has no effect on the tone. Therefore, the alphon and the experimental horn with their straight axes of tubing produce the same tone as the round wound French horn [picture 13].

According to Bahnert, Herzberg and Schramm, a too narrow mouthpipe or a too wide bell make the higher harmonics too flat; in the opposite case the harmonics become too sharp. Too small a cross section at the central part causes the middle registers to be too flat. In the case of tubing without a bell, i.e., an exactly cylindrical pipe, the high registers stay too sharp in comparison with the low registers. From past experience, the instrument maker can make the inside shape of the tubing so that the octave, fifth and third of its harmonics will be more or less in tune. In this way, bad intonation can be avoided. This comes from the opposition of the character of the natural tone scale against the harmonic cleanness of the chords. Before Bach the problem of tuning was grasped and as a practical compromise the tempered scale was introduced in which the frequency of each tone does not exactly match the natural tone series. It would be diverging too far from this subject to treat the details of this problem here. It must of course be noted that the orchestral instrument was played primarily in the natural scale, not in the tempered scale. It is a basic rule of acoustics that

every horn, for example, produce the minor or major whole tone according to the concerned note in the scale between 8. and 9. or between 9. and 10. harmonics. In the tempered scale there is only a whole tone. The accuracy of tuning for an orchestra depends upon the ability of each musician who must bring the tune of his instrument at every moment to the musical requirement. The hornist, for example, knows his instrument and corrects the tones, if necessary, before they are produced by changing his embouchure. The right hand in the bell is also helpful; when the bell is closed, the tone becomes flat and when opened it is sharp. With this explanation, it may be briefly pointed out how complicated and delicate is the tuning of a horn for playing in an orchestra.

The physical characteristics of the horn which produce the natural tone series are explained in picture 10. At the fundamental, the first natural tone, the node of vibration locates in the lips or very near them and the loop is in the bell [picture 10, the lowest curve]. Only a quarter of the total sound wave locates in the horn. This is called the first vibration stage. When the lips are given some tension, the second natural tone of one octave higher sounds. In the tubing, the second node is built and it controls the second vibration stage [picture 2, the second lowest curve]. It is also called the first overtone. We avoid this expression because the first overtone is the second natural tone and both expressions are easily confused. With the increasing tension of the lips, natural tones of 3. 4. 5. and so on, with their correspondingly higher vibration stage and number of nodes, are produced successively. Their curves

are in picture 10, one upon the other. The transformation of a natural tone to a higher one is called overblowing. The woodwind instruments are also overblown; with the flute it is the same but with the clarinet the 3rd vibration stage is produced by the help of the register key, where the 12th, the 5th over the octave, sounds.

The notes of the scale which locate between two natural tones can be produced two different ways. Both ways consist of changing the acoustical length of the tubing through which the frequency and the height of the tone are shifted. This is no different from tuning the pitch of the instrument by changing the length of the tubing.

The steps of the tonal scale of woodwind instruments are achieved by shortening the tubing by opening the holes which are covered by the fingers or keys and thus the vibrating air column is shortened. It is analogous to producing the tonal scale on the violin, i.e., but putting the finger on the string, the length of the vibration is reduced.

With brass instruments the tonal scale is achieved by lengthening the tubing through additional pipes or valves and then the frequency drops and the tone becomes flat. With the slide trombone, elongation is made by the slide. Today in the popular instruments with valves, the second valve lowers the tone one-half tone, the first one whole tone and the third a minor third. Through the combination of valves, one can produce the major third, fourth and over fourth to cover the fifth between 2. and 3. natural tones chromatically.

## 2. The Sound Spectrum

So far an explanation has been given about the vibration of the air but only one frequency has been treated. Actually, the vibration of the air in blown instruments is a combination of many different frequencies. As the acoustician, Hermann Helmholtz (1821 to 1894) discovered 100 years ago, the sound of the human voice and the sound of musical instruments consists of a superimposing of various tones with different frequencies. The sound produced by a tuning fork or generated by an electric frequency generator has a pure single frequency tone and to the human ear it is colorless. As sunshine is a mixture of the rainbow colors, the sound of instruments and the human voice is a combination of different frequencies. Human ears classify sound according to its lowest frequency of vibration even if the harmonic of this frequency has less loudness than the higher harmonic. A sound is divided into its harmonics by a frequency analyzer. In picture 6, the 2nd natural tone of the F horn is shown. It is written C in the key of F and has a frequency of 88 Hz, according to Dr. Jürgen Meyer. Above the spectrum, the harmonics are marked in the tonality of F. Their frequencies correspond exactly to the multiples of the fundamental vibration. The characteristics of the tones in the natural tone series, as explained before, depend on the inside shape of the tubing being made to the exact dimensions of that specific instrument. The tone in picture 6 is clearly divided into 15 harmonics where the levels of 2. to 9. harmonics are higher than that of 1. harmonic. The human ear divides



a sound, which is a combination of vibrations with various different frequencies, into the single frequency analogous to Fourier analysis and distinguishes the tonal color according to the relative levels of the harmonics.

When we referred to the loop and node of vibration and wave length, we treated only a single harmonic with a certain frequency. When measuring sound pressure, the intended harmonic is also filtered by the spectrum analyzer and the total characteristics of its sound pressure (lengthwise in the instrument) is measured by the frequency counter as a curve. [See pictures 9 and 10]

Generally the characteristic of 1. harmonic of different natural tones is measured. Also 2. and 3. harmonics are recorded and each is shown in picture 12.

#### D. THE APPARATUS FOR RESEARCH AND PERFORMANCE

The alternation of sound pressure lengthwise along the axis of tubing, through which the characteristic of the standing wave is determined, can be recorded by a microphone and control unit. A small pipe with a microphone outside is lead into the horn at a certain place with pressure fluctuation so that the oscillation of the inside tubing is not disturbed by the microphone body. In order to lead the straight probe tube to every place in the horn, the instrument was made with a straight axis. Picture 13 shows this straight experimental horn in the key of F, together with an Inventionshorn of Raoux (Paris) from 1819 in the same key. Both horns produce identical natural tone series.

Picture 7 is the probe tube microphone (Sondenmess microphone) of Sennheiser Electric Company, Bissendorf, which is mounted on the traversible cart and connected to the control and recording apparatus by a cable. By the side of the cart, on the base, there is an iron bar with contact pins at every 100 mm. A contact is on the cart and when it is touched by a contact pin, a mark is recorded on the register strip corresponding to the displacement of the probe in the horn at every 100 mm. The microphone has a probe tube of 8 mm diameter which is extended by the measuring tube of 5 mm outside and 4 mm inside diameter. In order to check all the influences of the probe tube on the measured data, the measuring was also conducted using a smaller tube. To further check whether a disturbance by the tube inserted throughout the total length of the instrument does exist, the experimental horn was bent  $30^\circ$  at a place 1276 mm from the mouthpiece and the probe was inserted at this point. In this way the length with the disturbance inside was reduced by more than half. From all of these test measurements, no differences were recorded by the 3.7 m long probe tube with 5 mm diameter.

In order to cut out the fluctuations of a person blowing, the tone was produced as an experiment by a speaker which was fixed to the mouthpiece and driven by a generator. Owing to the problem of coupling and the different kind of vibration, it showed the displacement of the position of the vibration node in comparison with the blown one.

For this reason, in the final experiments all the tones were blown. Even if the small fluctuations of level of tone and frequency were unavoidable, the mean values were determined by repeating the record many times. In this way, a sound pressure curve with sufficient accuracy for our object was obtained.

Picture 8 shows the arrangements for this research and the people working on it. The writer is at the back of the horn as the blower. The man on the right side works with the recording strip of the level meter upon which the frequency counter is placed. To the upper right is a filtering apparatus through which the frequency of the registered vibration is filtered. The man in front controls the driving mechanism of the cart (a record player motor is connected to the cart by a thread). The man at the left records each measurement. A mute is inserted into the bell of the horn and through its center the probe tube is lead into the horn.

## E. RESULTS OF EXPERIMENTS

### 1. Characteristics of Sound Pressure in the Horn [picture 9]

On the ordinate, the sound pressure is recorded in logarithmic scale which the level meter has indicated. The curve consists, in its length, of three parts together because three probes with different lengths were adapted in order to record the sound pressure in the horn along its total length. A curve of arcade form is recorded and the loop of pressure or node of

vibration is at the top of it. The downward points of the curve are the location of the node of pressure or loop of vibration. Their distances from the mouthpiece are marked on the ordinate in regard to each vibration loop. The distance between two neighboring loops corresponds to a half wave length. Between the marked point on the abscissa, the numbers of double the product of the loop distance and frequency are noted. This number increases towards the bell. In the case of an open horn, the sound pressure sinks down into the sound pressure of the outside field continuously at the bell end surface. When a mute is mounted in the bell, the 8. loop of vibration is shown by the dotted curve and an additional 9. node of vibration arises in the closed wall of the mute. The measurements of sound pressure are not described because they are not necessary for our purpose. A pressure loop exists at the mouthpiece. Its level decreases in the following waves. The pressure at the bottom of the mute is remarkably little in comparison with the last maximum pressure in the horn. This may be attributed to the fact that the opening of the mute is smaller than the tubing diameter of the horn. The distance between the bottom of the mute and the vibration loop generated by the mute is smaller than a half of the previous loop distance because, according to Lord Rayleigh, the node between two loops is shifted in conical tubing towards its small end. This is also supposed to be the reason why the distance between the mouthpiece and the first vibration loop in the conical mouthpipe is larger than the half of that between 1. and 2.

loop. With regard to the slope of maximum pressure or minimum pressure, the writer has not found a conclusive explanation.

## 2. The Sound Pressure Curve of Natural Tones 1. to 6. in High F Horn [picture 10]

The length of the high F horn is half that of the normal F horn. With this horn, natural tone 1. is easy to produce. The pressure loop exists in the mouthpiece and the vibration loop in the bell. The horn contains only a quarter of sound wave at the natural tone 1.

The 1. harmonic was recorded in all the natural tones. The tubing of the horn is closed at one side; the acoustical "hard" closing exists at the mouthpiece. In contrast to the "gedackt" organ pipe where natural tones cannot be produced evenly, here an even number of tones are produced. The reason may be that the progressive conical shape of the bell produces different characteristic of vibration from the cylindrical organ pipe.

## 3. The Location of Vibration Loops for the Natural Tones of 2. to 12. in F Horn [picture 11]

All the recorded curves are harmonic 1. The sound pressure curves are not to be carried but the locations of their vibration loops are shown on the abscissa. The figures between two marked points indicate double products of distance and frequency at the corresponding place. The wave length is the distance between every other vibration loop. The product of wave length and frequency is the velocity of the sound wave. The figure which is introduced

through the calculation in the measured length of the horn deviates very much from the sound velocity in the open air. In the conclusion of this report, this point will be treated again.

Hitherto it was supposed that the middle vibration loop of an even number of the natural tone locates in the center of the instrument. At the same time, one supposed that vibration loops existed in the mouthpipe and in the bell. With regard to the mouthpipe, this assumption is wrong. The acoustical center is defined as a place where the middle vibration loop of an even natural tone or vibration node of an odd natural tone exists [as shown in picture 11]. The acoustical center deviates towards the mouthpiece from the geometrical center of the instrument. This tendency becomes greatest at the lowest natural tone and approaches more and more to the geometrical center with the increasing frequency.

#### 4. The Sound Pressure Curves of 1. 2. and 3. harmonics at the Natural Tone of 4. 6. 8. 12.

The combination of curves shown in picture 12 is an interesting result; at the same natural tone the locations of loops and nodes at the harmonic 2. and 3. do not correspond to those at harmonic 1. They have the same location as the harmonic 1. of a natural tone with higher frequency. So the harmonic 2. of natural tone 4. with the frequency of 356 Hz has the same location as the harmonic 1. of natural tone 8. with the same frequency. The harmonic 1. of the natural tone 12. with frequency of 534 Hz locates at the same place as harmonic 2. of the natural tone 6 and harmonic 3. of natural tone 4.

## 5. The Vibration in the Oral Cavity at Blowing the Tone

The method of voice production for singing is vitally related to the singer's body itself, i.e., the head, face, throat, chest and diaphragm which is regarded as a prop. Some famous hornists hold the opinion that analogous to the singing voice, the vibrations of blowing the horn continue from the lips into the oral cavity and the air column extends into the chest. We tried to measure the sound pressure in the oral cavity by a probe tube which was introduced there around the mouthpiece and compared it with the sound pressure in the horn. This measurement showed a figure of a fraction of the sound pressure in the mouthpipe. No difference of sound pressure was found when the probe tube was shifted to change its location in the oral cavity. In the case of buzzing a tone without blowing, the sound pressure of the closed lips was almost the same as in the mouthpipe when blowing. When the mouth was opened, the sound pressure fell down to half of what it had been. The sound pressure was, in this case, still almost as large as twice that generated by blowing without buzzing. Hence, it is concluded that no standing or stationary wave is produced in the oral cavity by blowing and the vibration in the oral cavity vanishes when blowing a horn and therefore has no influence on the production of tone when blowing. The influence of the different tongue or palate positions on the blown tone seems to be caused by the different tension on the lips. This experiment could admittedly be evaluated as a trial research.

## F. SUMMARY and CONCLUSION

The results of this research are summarized as follows:

1. The characteristics of sound pressure along the longitudinal axis of the horn are shown as arcade form curves [pictures 9, 10 and 12] where the pressure loop (vibration node) locates in its maximum and the vibration loop in its minimum. The distance between them increases towards the bell. The pressure loop exists at or near the lips and the vibration loop exists in the bell. The comprehensive explanation for the characteristics of pressure of the different natural tones points out that the acoustical center of the instrument depends upon the frequency.
2. The additional pressure loop exists at the bottom of the inserted mute or at the hand inserted to "stopf." In the case of "Stopfen" by hand, the acoustical length of the horn is shortened so that the natural tone scale becomes one-half tone sharp. By operating the second valve or the stopf v alve, the acoustical length is increased to get the original tuning of the instrument.
3. In the case of the open horn, the minimum sound pressure at the last vibration loop does not exist; it appears in the sound pressure curve of the muted or "getopft" horn.
4. The harmonics with the same frequency have equal standing or stationary waves, independent of the natural tones from which they arose. The pressure loops and the vibration loops of different harmonics from the same natural tone are shifted against one another, except the first pressure loop and the last vibration loop.



The questionable results of the research which need scientific clarification follow:

1. Maximum and minimum sound pressure increases regularly from mouthpiece to bell.
2. The velocity of sound in the tubing of the horn, when it is calculated as a product of wave length and frequency, does not correspond to sound velocity of 345 m/s at 22° C in the open field. In the case of the F horn, according to the results of the measurement in picture 11, it is at the conical mouthpipe of 9 mm mean I.D., 331 m/s, in cylindrical tube of 12 mm I.D. 335 m/s and in conical branch and bell 350 to 390 m/s. The doubled product of loop distance and frequency is in the narrow tube smaller and in the wide, conically progressive tubing, bigger than the sound velocity in the open air. The sound velocity in the tubing can be influenced by:

- a. the temperature of the air (tuning of a cold wind instrument is always flat, so it is warmed up before a concert by blowing).
- b. the content of moisture and carbon dioxide in the air
- c. the velocity of the air (The volume of air blown at Forte is about 0.5 L/s. This volume generates in a cylindrical tube of 12 mm I.D. a speed of 4.4 m/s.)

These three physical factors (a, b, and c) could have a much smaller influence on the distance between the vibration loops than that of the geometrical form of the tubing. This coherence is proved by the fact that when a tone is produced by blowing at the open end of a bottle or tube with different cross

sections and closed ends, the multiples of its frequency and four times bottom distance have a deviation far from the sound velocity. It is especially interesting that the tone from a conical tube with one side closed is different, depending upon whether it is blown at its small end or large end. A lower tone is produced when the tube is blown at its small end.

At the end of this report, it is to be mentioned that Lenco Company, Burgdorf, has helped the writer to furnish his acoustical laboratory with excellent electronic equipment and that engineers, Mr. B. Strausak and Mr. Rud. Laeng, assisted the writer with their technical knowledge. The writer would like to express his thanks to them.

#### Bibiligraphy

- [1] Meyer, Jürgen: Akustische Untersuchungen über den Klang des Hornes. "Das Musikinstrument" 12 (1967), H. 1 und 2, S. 32-37 und 199-203.
- [2] Krüger, Walter: Objektive Untersuchungsmethoden bei Metalblasinstrumenten. "Das Musikinstrument" 13 (1968), H. 3, S. 459-462.
- [3] Lord Rayleigh: The Theory of Sound. New York 1945, Dover Publications, erste Ausgabe nach der revidierten und erweiterten Auflage von 1894.
- [4] Bouasse, H.: Instruments a Vent. Paris 1929, Librairie Delagrave.
- [5] Trendelenburg F.: Einführung in die Akustik, Berlin, Göttingen, Heidelberg 1961. Springer-Verlag.
- [6] Bahnert, Herzberg, Schramm: Metallblasinstrumente. Leipzig 1958. Fachbuchverlag Leipzig.

*George William Hegre*

DEDICATED

TO

RENOLD O. SCHILKE

ACOUSTICS OF THE FRENCH HORN

by

DR. WILLI AEBI

for the

French Horn Workshop  
Tallahassee, Florida  
June 1970

## ACOUSTICS of the FRENCH HORN

by Dr. Willi Aebi

The raw material of music is sound produced by the human voice or by music instruments. Depending on the way sound is produced, we distinguish the following music instruments: percussion instruments, string instruments and wind instruments. Within the wind instruments there are two groups: firstly, woodwind instruments, including also the flute and the saxophone nowadays built in metal, and secondly, brass instruments where the sound is produced by passing a fine air stream through the lips placed across the mouthpiece. The column of air in the tube starts vibrating and the vibration, partly propagated in the ambient air, reaches our ear and is perceived by our sense of hearing as a tone.

Sound, as we hear it, is the result of pressure fluctuations which are propagated in the air. The bang of a rifle travels at a speed of 343.8 m/sec [1128 ft/sec] at an air temperature of 20° Celsius. This is called velocity of sound. When the pressure waves are periodical, the sound is perceived by the human ear as a tone having a certain pitch. The lowest discernible pitch has around 16, the highest about 20,000 vibrations/sec. The concert pitch "a" has a frequency of 440 vibrations/sec.

The distance between two tones, that is the musical interval, is determined by the ratio of frequencies of the two tones. The basic musical interval is the octave

which has a frequency ratio of 2:1. For instance: two tones having a frequency of 100 and 200 vibr/sec respectively are an octave apart just as two tones having a frequency of 5000 and 10,000 respectively. The importance of the French Horn is due to the fact that you can blow on it the harmonic series (fig. 1) which includes the harmonic chord. The frequencies of the harmonics are always in ratios of simple whole numbers: octave 1:2, fifth 2:3, fourth 3:4, major third 4:5, minor third 4:6, etc. From these ratios results the harmonic scale in opposition to the equal temperament scale, where the twelve semitone steps of the chromatic scale within an octave have the ratio 12th root of 2 equals 1.0595. The semitone step from the 15th to the 16th harmonic scale, the leading note lies obviously lower than in the tempered scale. With the exception of the octave, there are differences of frequency between the harmonic and the tempered scale. These facts cause problems that are of special importance for a musician in an orchestra. Time does not permit to enter into these very interesting but very complicated questions.

As was mentioned before, the octave of the tempered scale has 12 equal semitone steps where the number of vibrations from one tone to the next has the ratio twelfth root of two. This is the factor by which the frequency of one tone has to be multiplied to get the frequency of the next higher tone. Going through the whole chromatic scale of an octave, you have to multiply twelfth root of two twelve times by itself. In mathematics this reads: twelfth root of two to the power of 12. The result is 2 which is the ratio of an octave.

In my opinion the musician in the orchestra intonates his instrument in the harmonic and not in the tempered pitch because our sense of pitch is harmonic.

Figure 2 represents the results of the calculation of the frequencies of the 8th to the 16th harmonic on the F-horn compared with the frequencies of the tempered scale when we are basing on concert pitch "a" with a frequency of 440 vibr/sec.

As we are basing on the concert pitch "a" with a frequency of 440 vibr/sec the fundamental tone  $f'$  of the horn is slightly higher in the harmonic scale compared with the tempered scale. If we based on the same fundamental tone  $f'$ , the third on the F-horn, which is blown e", that is the tenth harmonic, would be slightly too low compared with the tempered scale. Therefore, the horn player does not play it as an open tone, but with the aid of valves, for instance the first and second valve. On the double horn I always blow this tone on the B-flat-horn with the second valve, hence as eighth harmonic on the A-horn.

On all brass instruments the system of the three valves causes a lot of difficulties especially when a combination of various valves is used and also because of the differences of pitch in the diatonic scales of the various keys. Every player of a brass instrument has to make adjustments with the embouchure following his sense of pitch. The horn player can also make these adjustments with his right

hand in the bell. Dr. Vogel\* treated these problems very thoroughly in his essay, "The Intonation of Brass Instruments," and he also made technical proposals for valves of variable length, but they proved too complicated and could therefore not be put into practice. For the sake of completeness, I'd like to mention that there are tubas on which, when using a combination of various valves, additional crooks are introduced. But this correction too is not perfect.

The fundamental question whether the orchestra should at all strive at playing in the tempered pitch and whether this would be possible has never yet been treated by experts, as far as I know.

After these general remarks, which could of course be expanded in many directions, I come to the main object of my lecture; my experiments concerning the vibrations within the tube of the horn.

Talking of the acoustic fluctuations of air motion and air pressure of a tone, we have to distinguish between the vibrations of the air particles around a given point and the propagation of these vibrations to neighbouring air particles. This latter process gives the propagated sound wave and can be compared to the wave on a water surface. As was mentioned before, the sound wave travels at a speed of 343.8 m/sec [1128 ft] at a temperature of 20° Celsius. An acoustic source

---

\*Martin Vogel: "Die Intonation der Blechbläser," volume I of the ORPHEUS - series published by Gesellschaft zur Förderung der systematischen Musikwissenschaft, Dusseldorf, 1961

which produces a tone of given pitch performs say 100 vibrations in a second. The first of these vibrations has travelled 343.8 m [1128 ft] during this second, the latter 99 vibrations correspondingly less. Each vibration forms a wave which has a length of 343.8 [1128 ft] divided by 100 equals 3.438 m (11.28 ft) divided by 440 equals 0.78 m [20.7 ft]. With all tones, the product of wave-length multiplied by frequency is the velocity of sound.

In acoustics, we distinguish between propagated waves as just described and standing waves. The common idea is that the standing waves are the result of superimposition of propagated waves of equal frequency moving in opposite directions. They are produced generally only within a limited space at the boundaries of which reflection occurs. The vibration produced in the lips travels through the tube to the bell, is reflected there and travels back into the tube. The result of this process is a superimposition of propagated waves which gives the standing sound wave. In order to get a clear idea of the standing sound wave, let's look at the vibration of a string on the violin, as illustrated in figure 3.

The string is fastened at both ends and we call these fixed points vibration nodes. If we pluck the string at the center point it will vibrate in the form of a bow along its whole length, that's the first node of vibration. The motion is transversal to the string. The center point, where there is the largest amplitude, is called vibration loop. The same node of vibration can be produced by applying the violin bow on the string next to the bridge.



By putting the finger lightly on the center of the string, a node is produced there.

The two halves are opposed in phase. That's the second mode of vibration and we hear the octave of the fundamental tone.

If again we put down the finger lightly at one third of the length of the string, we hear the fifth above the octave; this is the third mode of vibration.

Analogously, we can make the string vibrate in four parts and this is the fourth mode of vibration, and we hear a tone two octaves above the fundamental tone.

The air particles of the standing waves in the tube of the brass instruments move longitudinally to the axis of the tube. As on the string, in the tube too, various modes of vibration are possible. Let's take the first mode: the tube is open at both ends, the air particles vibrate in both ends at a maximum amplitude in opposite phase. In the center of the tube, where there is the vibration node, the air particles are at rest, since the two halves of the air column vibrate in opposite phase. When the air particles are at the innermost point, they press towards the center intensifying the pressure there. When they are in the utmost ends, the pressure in the center is at a minimum. The fluctuation between the minimum and the maximum pressure is called sound pressure. In the vibration loops the pressure does not change; there the sound pressure is at a minimum. With the first mode of vibration, there is only half a standing wave between the two ends of the tube.

On figure 4 you see a simplified presentation of the second mode of vibration in a tube open at both ends. In the two ends and in the center, the air particles vibrate at maximum amplitude in the two ends synchronously but in the center in opposite phase. These are the three vibration loops of a whole sound wave. At the distance of a quarter from the ends of the sound wave, at the vibration nodes, the air particles are at rest. The upper curve on figure 4 indicates the motion of air particles vibrating in the horizontal axis. The lower curve shows the distribution of pressure. As was mentioned before, the fluctuation between pressure maximum and minimum is called sound pressure. In the vibration loops at the ends and in the center the pressure is zero, that is: where we have a vibration loop, we have a pressure minimum, conversely at one quarter and three quarters of the length where we have a vibration node, we have a pressure maximum. This pressure distribution along the axis of the tube may be measured by means of a microphone and registered as a curve via an electrical apparatus. The curve of the pressure distribution gives us an idea of the standing acoustic wave in the tube.

Up to now we talked about the vibration of the air particles as if it were similar to the simple vibration of a pendulum. But that's not so. The actual motion of an air particle is a superimposition of several vibrations of various frequencies.

A hundred years ago the German acoustician Helmholtz found out that the sound of the human voice and the sound of a music instrument consist of a superimposition

of a number of different simple tones. But these tones are not arbitrary; on the contrary, they appear in the same order as the harmonics on the brass instruments as shown on figure 1. Above the fundamental tone lie the overtones whose frequencies are whole multiples of the fundamental tone. They are called partial tones because they are part of a whole sound.

Figure 5 represents the partials of the second harmonic blown on an F-horn; it sounds F and has a frequency of 88 vibr/sec. The partials 2 to 8 show a higher sound pressure than partial 1. In different notes the relation of the sound pressure of the partials to that of the fundamental varies. In the higher register the first partial has the highest sound pressure. When doing our measuring, we have mostly registered the variation of sound pressure of the first partial along the longitudinal axis of the horn.

It would be very difficult to slide a microphone through the looped tube of the horn. I therefore used for my experiments a horn with a straight axis, specially built for that purpose, as shown on figure 6. For the sake of comparison you see in the same picture an Invention Horn constructed in 1819 by Raoux, Paris. Both horns are in F and have a length of 3.7 meters [11.31 ft]. The inside diameter of the cylindric tube is 12 mm [.47"]. That's too narrow to introduce a microphone. I therefore lengthened the probe of a probe-microphone by means of a tube with a diameter of 5 mm [.197"]. The sound pressure at the end of the probe tube is transferred through the bore to the microphone which is fixed on a little wagon (fig.7).

The electrical vibration in the microphone is transmitted by a cable to the apparatus which records on paper the distribution of sound pressure along the longitudinal axis of the horn. The whole experimental layout is shown on figure 8.

One could also produce the tones at the mouthpiece by means of an electrical loud-speaker. But comparison showed that the standing waves of the electrically produced notes don't coincide with those of the blown tones. Therefore, I blew all the tones we tested myself.

Figure 9 shows the curve of sound pressure of the 8th harmonic blown on the F-horn; it sounds  $f'$  and the first partial has a frequency of 356 vibr/sec.

The curve has the form of arcades whose tops descend slightly from the mouthpiece to the bell. In the uppermost points of the arcades lie the pressure maxima, the pressure loops or vibration nodes and in the lowest points lie the pressure minima, the pressure nodes or vibration loops. In order to avoid confusion, I will from now on use the terms loops and nodes only in connection with vibrations; in connection with pressure I'll talk of maxima and minima. The positions of the loops and nodes can be measured fairly accurately. Their distance from the mouthpiece is indicated at each ordinate. The difference between two neighboring values is equal to half the length of a whole standing wave. The wave length increases by approximately 10% from the mouthpiece to the bell. As we explained earlier, the product of wave-length multiplied by frequency equals the

velocity of sound. The value that we calculated in this way is not the same as the velocity of sound in open air. Whether it does in fact correspond to the local velocity of sound in the tube, is a question which is still hotly debated among my collaborators. For the following, we assume that it does. The velocity of sound in the tube is indicated between the marked points on the abscissa. Near the mouthpiece and in the adjoining cylindrical part of the tube it is considerably lower than in open air. I have so far not found the explanation of this fact; neither have the scientists that I consulted, but it must be possible to find it one day. The moisture and the increased content of carbonic acid in the exhaled air have a certain influence but this is so small that it can be ignored.

Examining the curve we find that there is a node in the lips and a loop in the bell. The exact position of the last loop cannot be read from the curve as the curve slopes constantly towards zero. Introducing a mute in the bell that does not change the pitch, the last loop appears in the curve as a peak pointing downwards and from there the curve rises to an additional node at the bottom of the mute as the dotted curve on the diagram shows (fig. 12). This, incidentally, explains the phenomenon of stopping by which the pitch is raised by half a tone. I am very pleased about this result since even Morley-Pegge says in his excellent book, "The French Horn": "For all their laboratory paraphernalia none of the acousticians has offered, as far as we know, a convincing explanation of the rise of pitch that occurs when we "stop" a note."

We have to distinguish three different cases: firstly, the use of a mute that does not change the pitch, secondly, stopping with the hand or a ball or a stopper made of cloth, which raises the pitch by half a tone and thirdly, partial handstopping which lowers the pitch down to a whole tone or more. This latter technique was the epoch-making discovery of Anton Joseph Hampel around 1750. It made it possible to close the gaps in the scale between the harmonics on the horn although at the cost of a considerable change of tone timbre. Thus the composers of the Mannheimer Schule and those of the classic and romantic era had an almost perfectly chromatic French Horn at their disposal.

In the muted horn, in contrast to the open bell, the vibrating air column is bounded by the bottom of the mute. At this boundary, the air particles cannot vibrate longitudinally; they are at rest and form a node with maximum pressure fluctuation. The length of the standing wave in the horn is not altered compared with the open horn and therefore frequency and pitch aren't either. Likewise, complete handstopping causes a node in the palm. But this node, compared with the one at the bottom of the mute, is shifted into the bell by approximately the length of the second valve. The length of the vibrating air column is thus shortened. By the use of the second valve, it is brought back to its original length and we have again the original pitch. Partial closing of the bell with the hand does not cause an additional node, but rather lengthens the vibrating air column and consequently also the standing waves, and the result is a lowering of

the pitch. This lowering of pitch is rather difficult to control. The horn player has to make adjustments with the embouchure.

The last loop in the open horn, which does not appear in the curve, is of special acoustic importance. In this loop and in the adjoining area the standing wave gradually changes into the outer vibration field of the propagated wave. Further, it seems that the upper partial tones are formed in the bell. That's why the tone of a cylindrical tube without conical enlargement and without bell, like that of a water hose, is so thin.

Let me mention another phenomenon of acoustic importance. It strikes us that the distance between the last loop and the node at the bottom of the mute is considerably shorter, and the distance between the node in the lips and the next loop considerably longer than half the distance between the subsequent loops. Lord Rayleigh found the theoretical explanation a hundred years ago; he says that in a conical tube the node is not in the center between two loops, but is shifted towards the narrower diameter.

On figure 10 the positions of the loops of the harmonics 2 to 12 on the F-horn are indicated on the abscissa by little circles. When we registered these experiments, we recorded only the first partial of the sound, that is, we filtered out all the higher partials. The pressure curve itself is not indicated. The figures between the marked points represent the product of twice the distance

between two loops multiplied by frequency, that is the local velocity of sound. As I mentioned before, it differs considerably from the velocity of sound in open air which is 345 m/sec [1131.88 ft]. In the conical mouthpipe of an inside diameter of 9 mm [.35"], the average velocity of sound is 331 m/sec; in the cylindrical tube of an inside diameter of 12 mm [.47"], 335.5 m/sec [1101 ft] and in the bell and the adjoining conical part of the tube, 350 to 390 m/sec [1148 to 1279.5 ft]. Furthermore, it is interesting to see on figure 10 that the half-way loop of the even numbered harmonics does not coincide with the half-way point of the tube, but is shifted toward the mouthpiece, at most with the second harmonic, but less and less towards the upper harmonics.

Figure 11 represents the sound pressure of the first partial of the harmonics 1 to 6 on a horn in high F. The frequency of the first harmonic is 88 vibr/sec of the harmonics 2 to 6. It is the corresponding multiple of 88 vibr/sec. For instance, for the 6th harmonic, 6 times 88 equals 528. Below the curves of sound pressure represented by continuous lines are the curves of the vibrations represented by dotted lines. In the lips where there is maximum pressure we have minimum vibration, a node. In the pressure minima, at the peaks pointing downwards, are the vibration maxima, the loops. The dotted curves do not represent measured values but are drawn instinctively. They illustrate the velocity of vibration of the air particles at the moment they pass through their mean position. All air particles are in equal phase. That means they are all at the same time in the center or in the extreme position of the vibration, respectively. The direction



of the vibration is opposite on the opposite sides of the nodes. A whole standing wave extends from one loop to the next but one loop. At the two ends of a whole wave the air particles vibrate in one direction only, in the intermediate loop in opposite direction. In half a wave, bounded by two loops, the left and right quarter wave, which vibrate to and fro in opposite direction, meet at the intermediate node (fig.4). These opposed vibrations are indicated on figure 11 by arrows in the bows of the dotted curves. In all the bows above the abscissa, the air particles at a given moment vibrate in one direction, for instance to the right in the bows below, in the other to the left.

Looking again at figure 11, we see that with the first harmonic there is a quarter of a wave between the mouthpiece and the last loop in the bell (which appears only when using a mute), with the second harmonic three quarters of a wave, with the third harmonic five quarters of a wave, with the fourth harmonic seven quarters of a wave.

I hope that my experimental investigations have helped in gaining a clearer picture of the shape and conditions of the vibration inside the horn. This was the main purpose of my investigations.

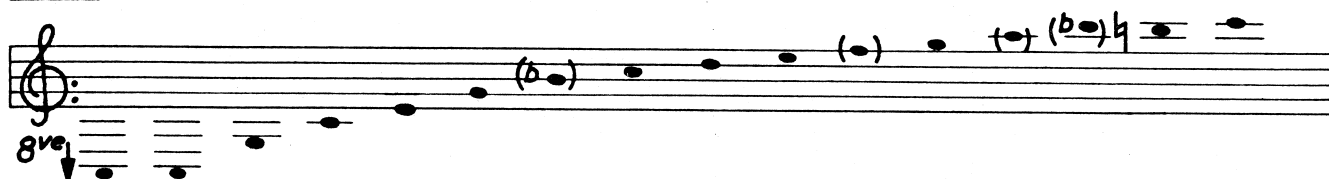
Figurenverzeichnis und Fachausdrücke  
 Catalogue of figures and technical terms

---

|        |                                                                                                                                         |                                                                                                                                     |
|--------|-----------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|
| Fig. 1 | Beilage 1 Bild 5<br>Naturtonreihe<br>Naturton<br>Klang                                                                                  | Ref.1 Bild 5<br>harmonic series<br>open note<br>sound, tone on the piano                                                            |
| Fig. 2 | natürliche Stimmung<br>temperierte Stimmung                                                                                             | harmonic scale<br>tempered scale                                                                                                    |
| Fig. 3 | Saite<br>transversale Schwingung<br>Schwingungsknoten<br>Schwingungsbauch<br>Wellenlänge                                                | string<br>transversal motion or vibration<br>vibration node<br>vibration loop<br>wave length                                        |
| Fig. 4 | longitudinale Schwingung<br>offenes Rohr<br>Schwingungsart<br>Druck<br>Schalldruck<br>Druckknoten<br>Druckbauch                         | longitudinal motion or vibration<br>open tube<br>mode of vibration<br>pressure<br>sound pressure<br>pressure node<br>pressure loop  |
| Fig. 5 | Beilage 1 Bild 6<br>Klangspektrum<br>Teilton, Teiltöne                                                                                  | Ref.1 Bild 6<br>spectrum of sound<br>partial tone, partial tones                                                                    |
| Fig. 6 | Beilage 1 Bild 13                                                                                                                       | Ref.1 Bild 13                                                                                                                       |
| Fig. 7 | Beilage 1 Bild 7                                                                                                                        | Ref.1 Bild 7                                                                                                                        |
| Fig. 8 | Beilage 1 Bild 8                                                                                                                        | Ref.1 Bild 8                                                                                                                        |
| Fig. 9 | Beilage 1 Bild 9<br>Verlauf des Schalldruckes<br>Bauchabstand<br>doppelter Bauchabstand<br>Schallgeschwindigkeit<br>Dämpfer             | Ref.1 Bild 9<br>curve of sound pressure<br>distance between 2 loops<br>double distance between 2 loops<br>velocity of sound<br>mute |
| Fig.10 | Beilage 1 Bild 11<br>mittlerer Schwingungsbauch<br>gerade Naturtöne<br>geometrische Mitte<br>Mundrohr<br>Anstoss<br>Schallstück, Schall | Ref.1 Bild 11<br>half-way loop<br>even numbered open notes<br>half-way point of the tube<br>mouthpipe<br>belltube<br>bell           |
| Fig.11 | Beilage 1 Bild 10<br>Schalldruck<br>Schwingung<br>Welle<br>Mundstück                                                                    | Ref.1 Bild 10<br>sound pressure<br>vibration<br>wave<br>mouthpiece                                                                  |
| Fig.12 | Schalldruck offen<br>" mit Dämpfer<br>" mit Handstopfen                                                                                 | sound pressure open<br>" " with mute<br>" " with handstopping                                                                       |

# Die Naturtonreihe des Hornes. Fig. 1

in F

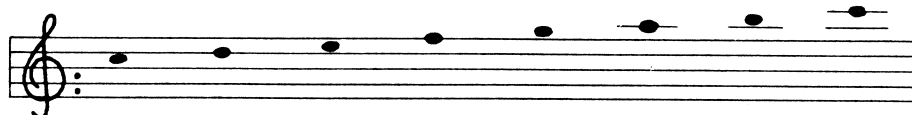


|          |    |    |     |     |     |     |     |     |     |     |     |     |     |     |     |      |
|----------|----|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|
|          | C  | c  | g   | c'  | e'  | g'  |     | c'' | d'' | e'' |     | g'' |     |     | h'' | c''' |
| Naturton | 1  | 2  | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  | 13  | 14  | 15  | 16   |
| Frequenz | 44 | 88 | 132 | 176 | 220 | 264 | 308 | 352 | 396 | 440 | 484 | 528 | 572 | 616 | 660 | 704  |
| Klang    | F' | F  | c   | f   | a   | c'  |     | f'  |     | a'  |     | c'' |     |     | e'' | f''  |

# Frequenz, natürliche und temperierte Stimmung.

Fig. 2

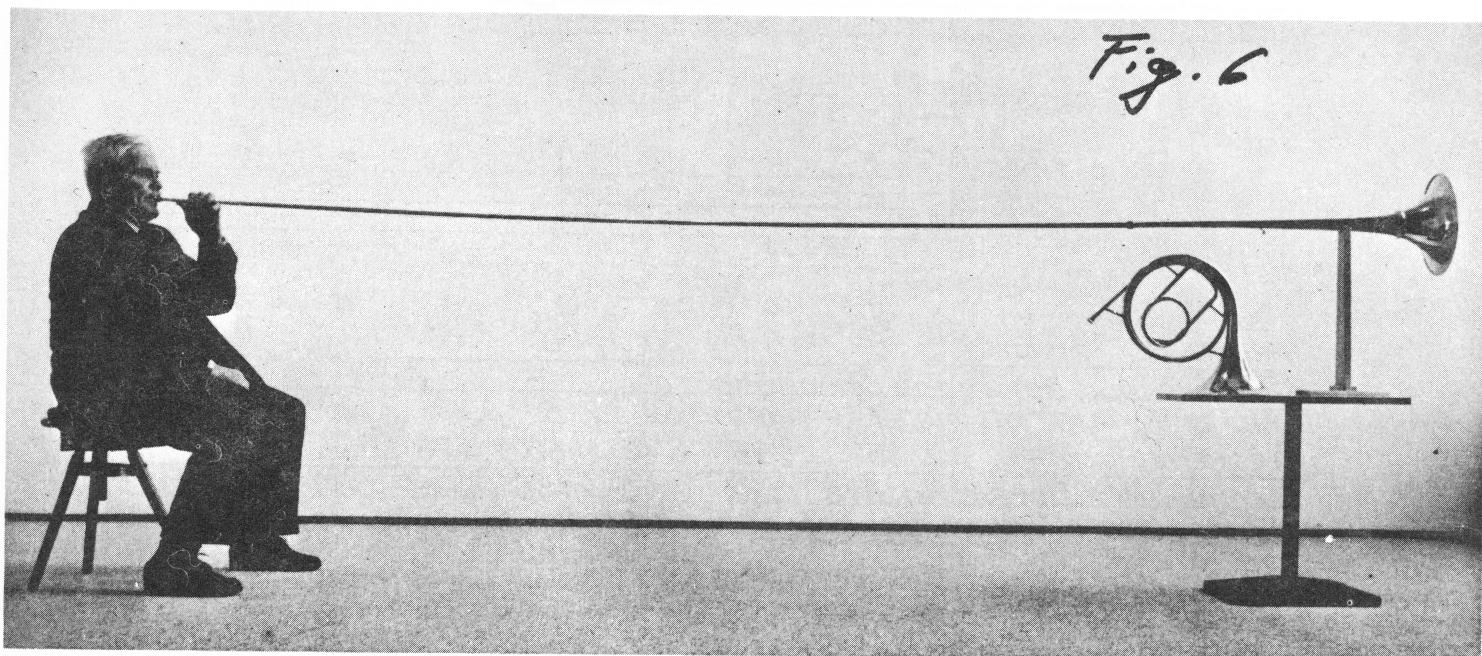
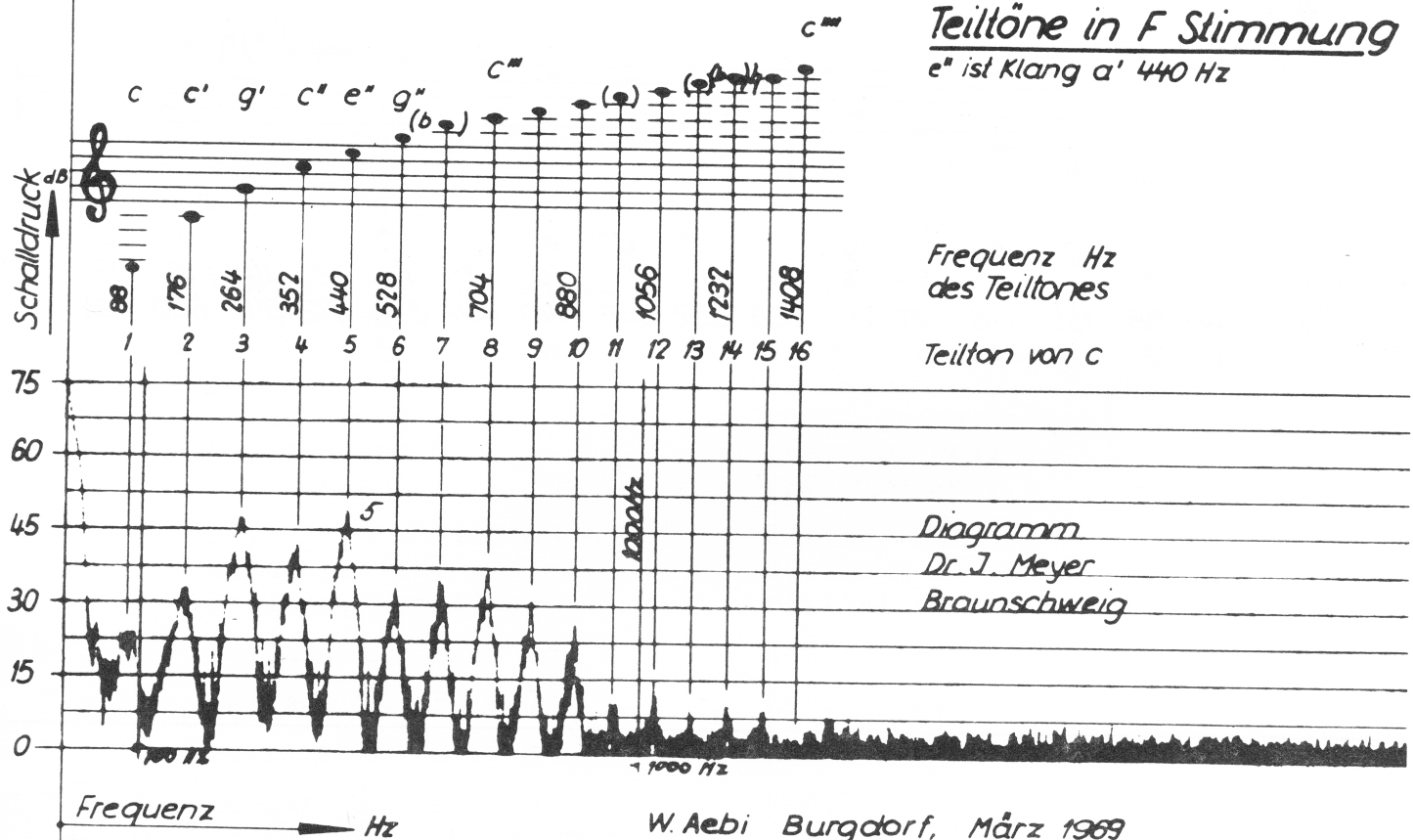
in F



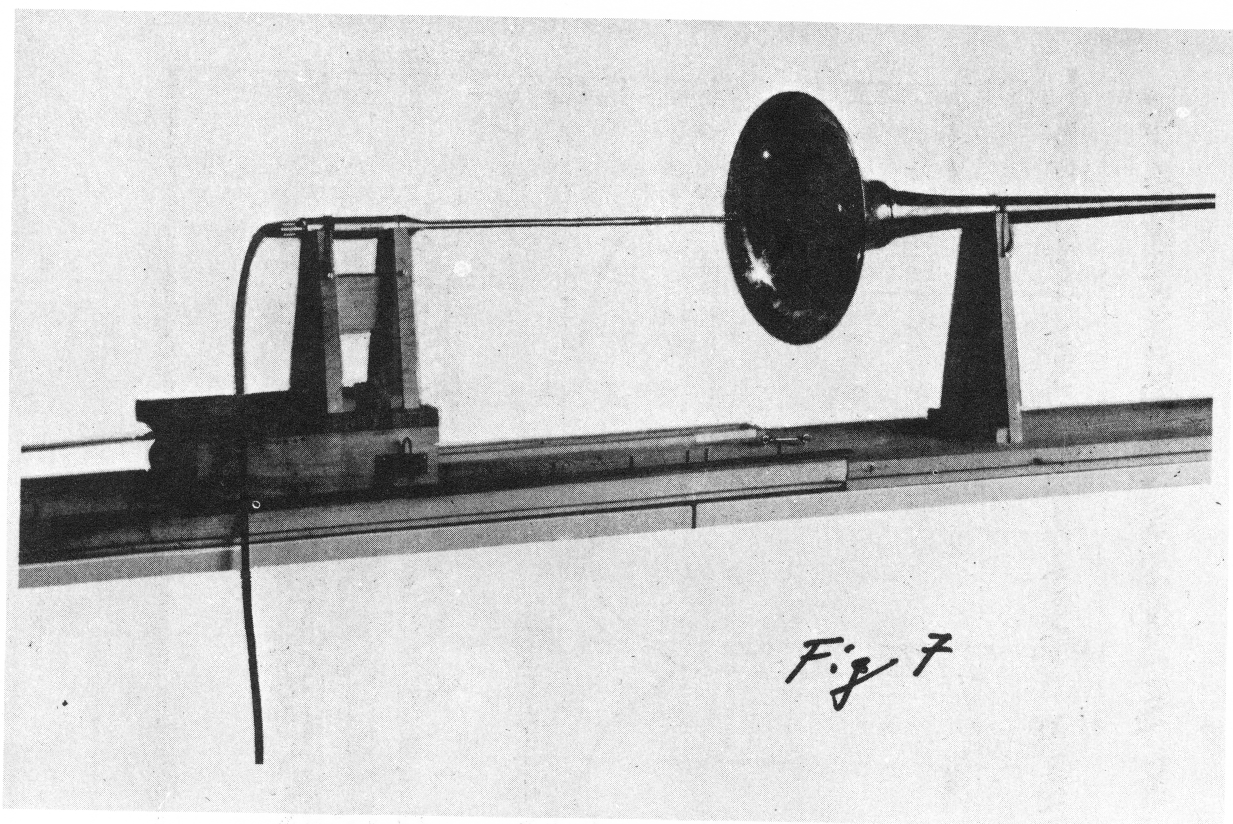
|                                   |     |     |     |       |     |       |     |           |
|-----------------------------------|-----|-----|-----|-------|-----|-------|-----|-----------|
|                                   | c'' | d'' | e'' | f''   | g'' | a''   | h'' | c'''      |
| Naturton F-Horn:                  | 8   | 9   | 10  |       | 12  |       | 15  | 16        |
| Klang F-Dur, natürliche Stimmung: | f'  | g'  | a'  | b'    | c'  | d'    | e'' | f''       |
| Frequenz:                         | 352 | 396 | 440 | 469,3 | 528 | 586,6 | 660 | 704 Hz.   |
| Temperierte Stimmung:             | 349 | 392 | 440 | 466   | 523 | 587   | 659 | 698,4 Hz. |

Fig. 5

Klangspektrum  
Horn in F 2. Naturton.





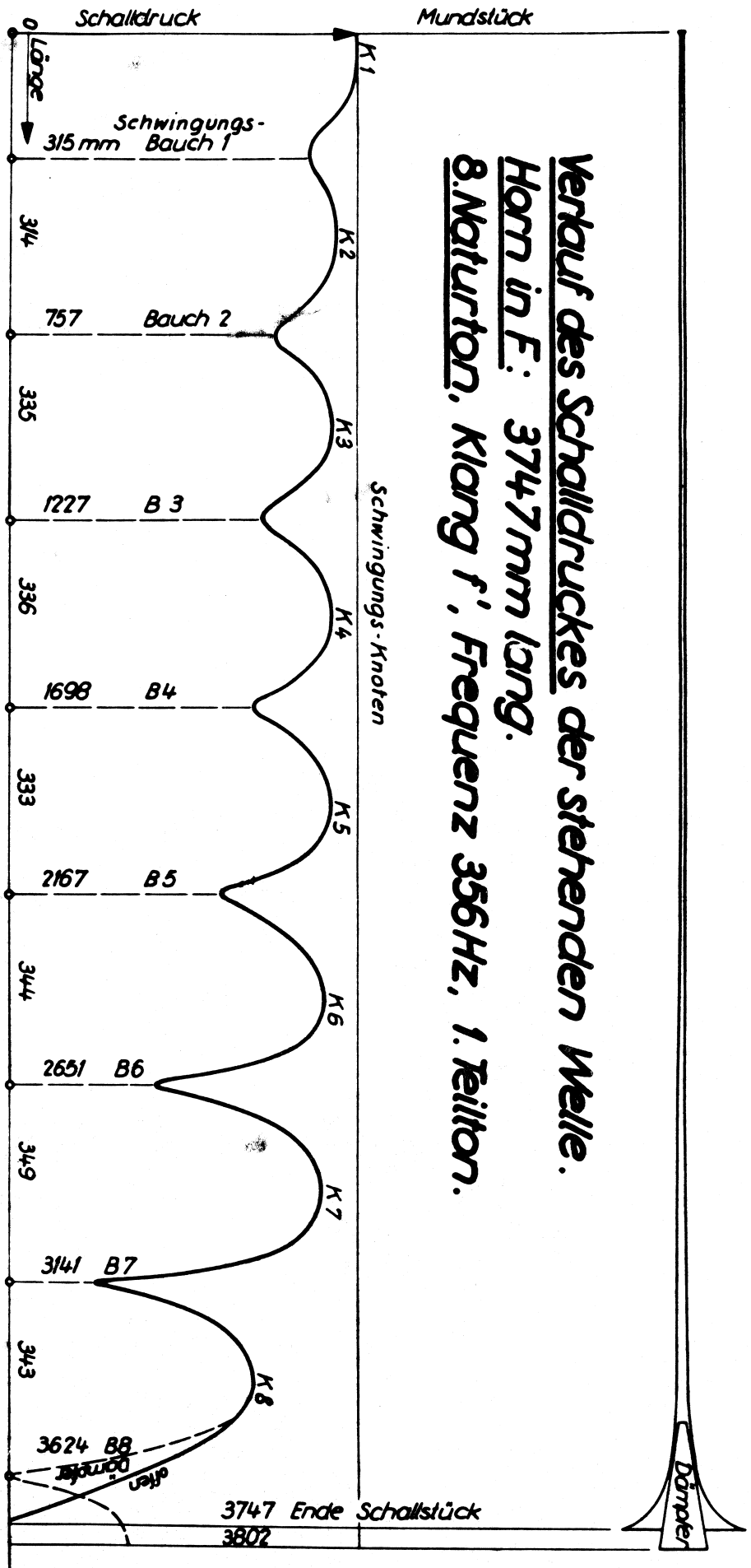


*Fig 7*



Fig. 9

Verlauf des Schalldruckes der stehenden Welle.  
Horn in F: 3747mm lang.  
8. Naturton. Klang f', Frequenz 356 Hz, 1. Teilton.

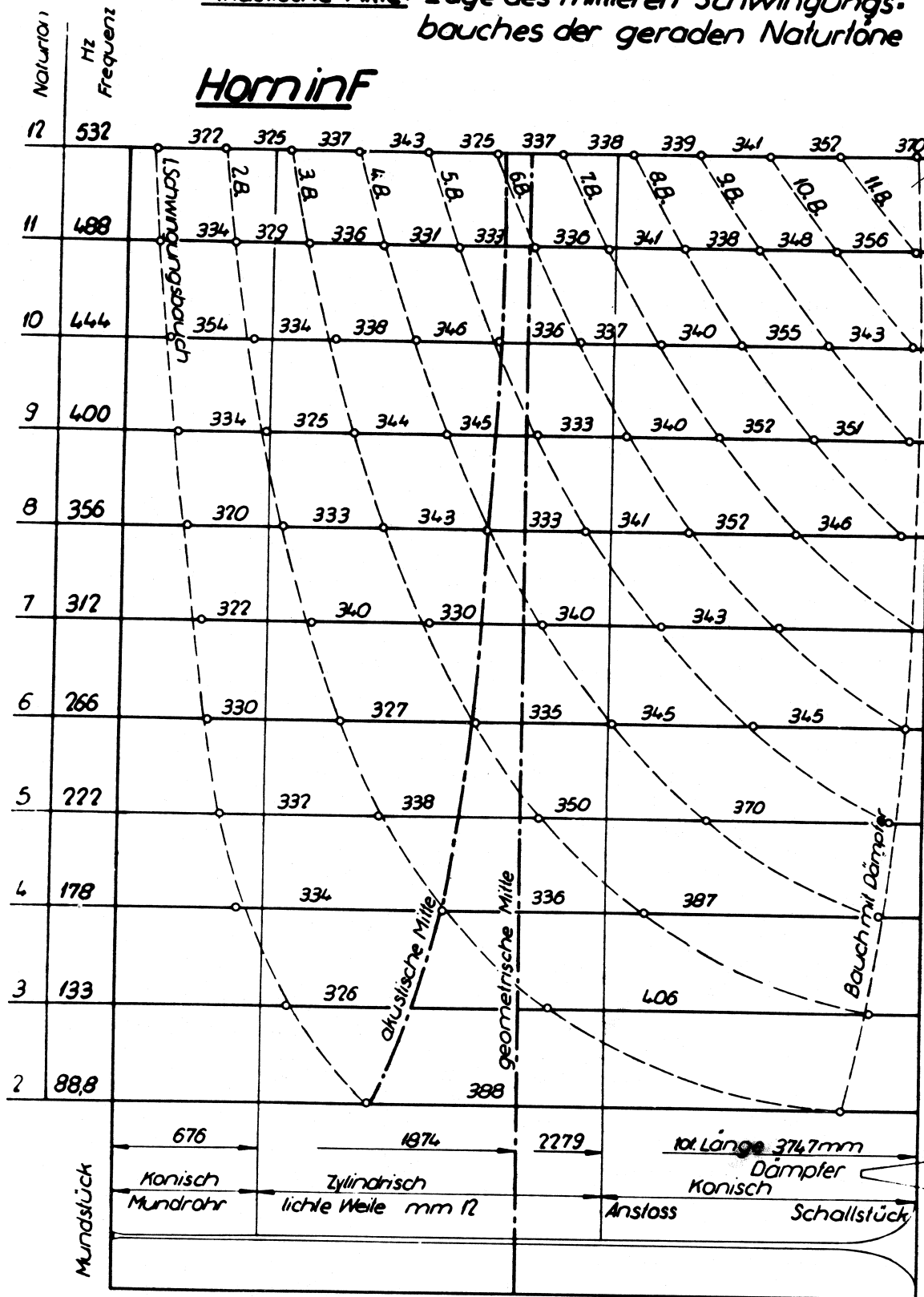


Zahlen zwischen den markierten Punkten: Doppelter Bauchabstand mal Frequenz.

Schallgeschwindigkeit in freier Luft bei 22° 345 m/sec

Akustische Mitte: Lage des mittleren Schwingungsbauches der geraden Naturtöne

Horn in F

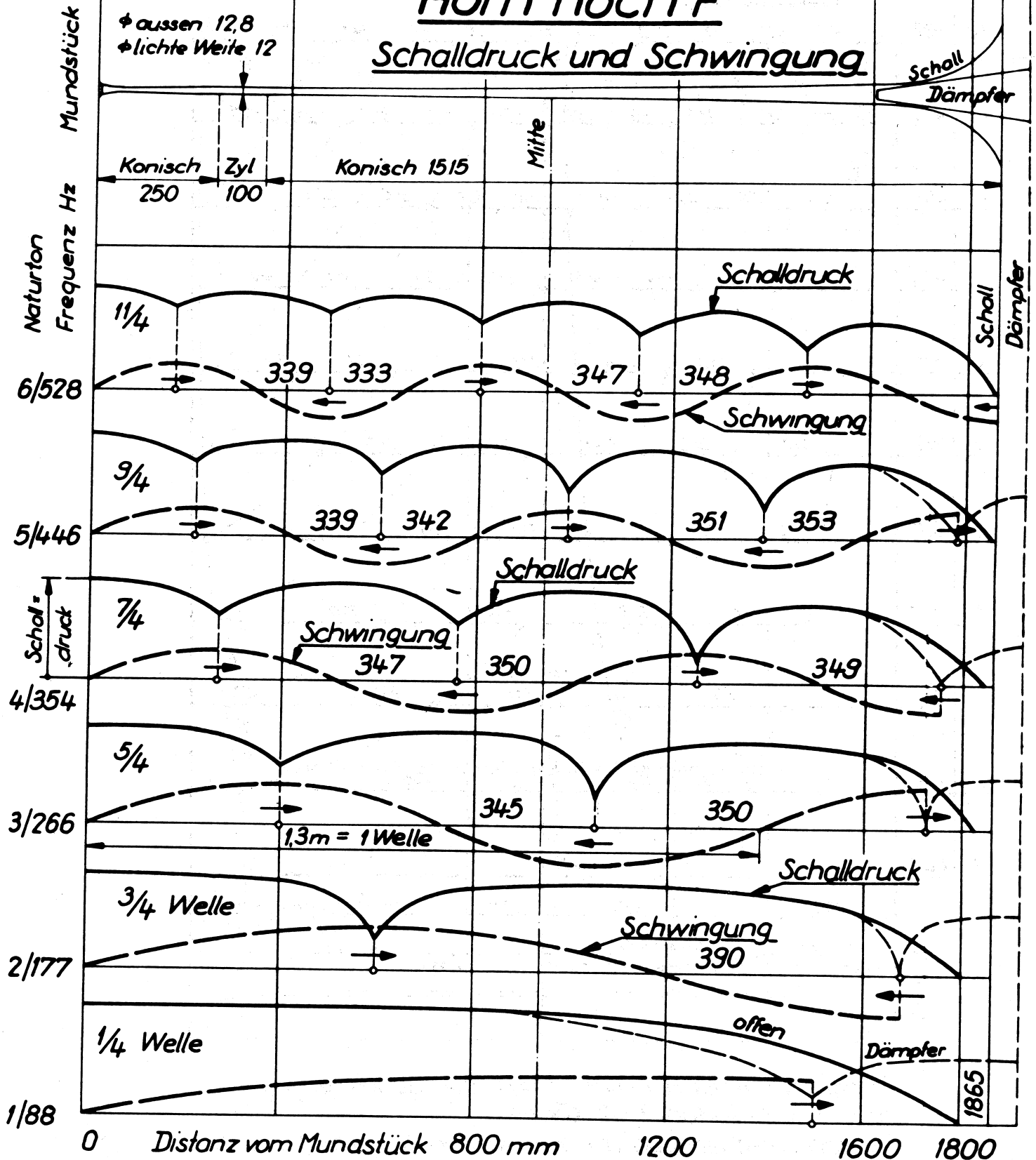


Punkte mit Kreis markiert: Lage der Schwingungsbäuche. Naturton 2-12, 1. Teilton.  
Zahlen zwischen den markierten Punkten: doppelter Abstand mal Frequenz. Schallgeschwindigkeit in freier Luft bei 22° 345 m/sec.

Fig. 10

# Horn hoch F Fig. 11

## Schalldruck und Schwingung





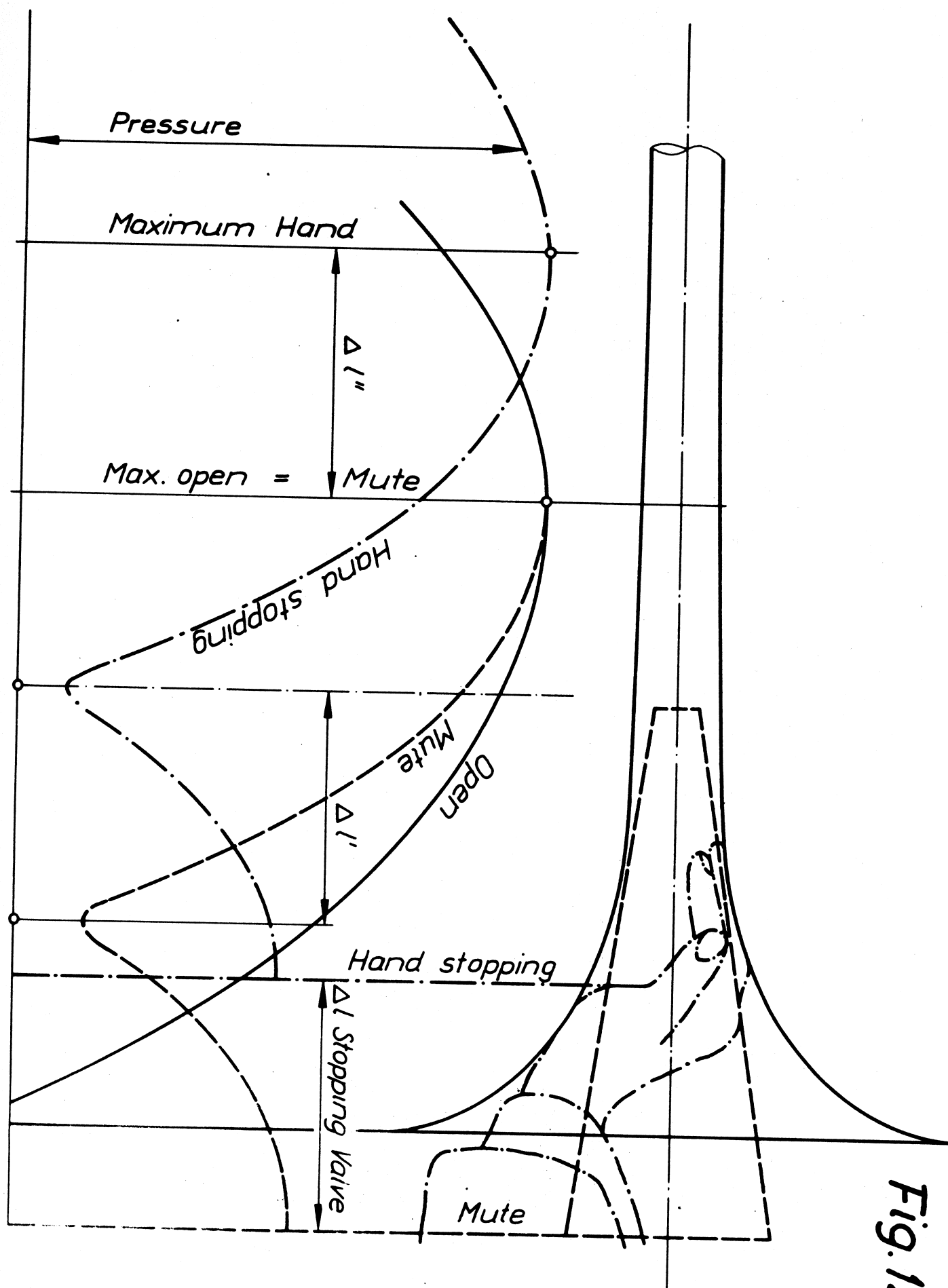


Fig. 12



Send for a FREE copy of The Schilke Brass Instrument  
and Accessory Catalog

**THE SCHILKE CO.**  
529 S. Wabash Ave.  
Chicago, Ill. 60605  
Tel. (Area code 312) — 922-0570